Building and Environment 46 (2011) 409–420

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

A rapid calibration procedure and case study for simplified simulation models of commonly used HVAC systems

Guopeng Liu [a,*], Mingsheng Liu [b]

[a] Pacific Northwest National Laboratory, P.O. Box 999, MSIN K5-16, Richland, WA 99352, USA
[b] University of Nebraska-Lincoln, Omaha, NE 68182, USA

ARTICLE INFO

Article history:
Received 3 June 2010
Received in revised form
3 August 2010
Accepted 5 August 2010

Keywords:
Calibration
Building simulation
Models
HVAC

ABSTRACT

A rapid procedure for calibrating simplified building energy simulation models of commonly used HVAC systems has been developed. The procedure developed will allow building professionals to project annual cooling and heating energy consumption of buildings with multiple HVAC systems from short-term field measurement data. This paper describes the general calibration procedure developed, and demonstrates the use of the calibration procedure by applying it to an office building. The calibration methodology requires as little as two weeks of measured hourly heating and cooling consumption data. In the example presented, the simulation model was calibrated using only two weeks of measured heating and cooling data. After calibrating the simulation using this procedure, the RMSE is reduced significantly. The simulation calibrated to two weeks of measured data is then used to simulate the hourly consumption of the building for the year 2004. Comparison of the results of this simulation with the measured data gave monthly CV(RMSE) values of 10.3% and 3.7% for cooling and heating, respectively, which are both well below the 15% values considered acceptable in ASHRAE Guideline 14 [1]. It also shows monthly NMBE values of 2.2% and 1.4% for cooling and heating respectively.

1. Introduction

Energy analysis plays an important role in developing an optimal HVAC and architectural design for new buildings and in determining optimal retrofit and commissioning measures for existing buildings. In most cases, computer simulations are required to develop an optimal design due to the complex nature of building energy systems, although manual hand calculations may be more suitable for some simple cases.

Before the 1960s, building energy calculations and system sizing were conducted using manual methods such as degree day, equivalent full load cooling, and bin heating/cooling methods if done at all. Automated calculation methods evolved over the next two decades, with first generation automated methods developed between 1965 and 1975, and with the second generation of automated methods developed between 1975 and 1983.

The second generation of automated methods includes both detailed simulation methods and simplified methods. Programs representative of detailed simulation methods are BLAST [9] and DOE 2.0 [16]. These programs are capable of considering a building's dynamic behavior using hourly simulations. However, detailed input information is required to produce correct output [15].

The ASHRAE simplified energy analysis procedure (called the modified bin method in this paper) is representative of the simplified methods. The modified bin method uses steady state analysis to determine the envelope heat transfer and internal gains and uses a simplified temperature dependent representation of solar heat gains. This enables the use of envelope inputs that are much simpler than those used in detailed simulation methods [14]. Significant effort and research have been conducted to compare the detailed and simplified methods over the last thirty years [4,15].

Calibrating computer models to actual metered data is not a new practice. As early as 1970, recommendations were made to calibrate models based on measured data [2]. Some researchers and engineers have attempted to compile "how to" manuals and methods in order to simplify this task [3,6–8,10–12,20,21,25]. Further, in almost all cases the end result falls short of a useful toolkit of procedures. Most of these calibrations rely on comprehensive simulation packages that model building energy flows and HVAC system performance in a more detailed manner than does the simplified systems approach. If the building has multiple HVAC units, models for each unit need to be formulated. This procedure is

* Corresponding author.
E-mail addresses: guopeng.liu@pnl.gov (G. Liu), mliu2@unl.edu (M. Liu).

0360-1323/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2010.08.002

Abbreviation list

CAV	constant air volume
CHW	chilled water
CV	coefficient of variance
HVAC	heating, ventilation and air-conditioning
HW	hot water
MBE	mean bias error
NMBE	nominal mean bias error
RMSE	root mean square error
RTD	resistance temperature detectors
SDC	single-duct and cooling only
SDH	single-duct and heating only
SZCAV	single zone constant air volume
VAV	variable air volume
WBE	whole building electricity

tedious and time-consuming for field application. Most of these procedures also rely on use of at least several months of measured data.

Liu et al. [18] studied simplified AHU model calibration using whole building cooling and heating energy consumption data. The study indicated that two-zone models work well provided that the interior and exterior zones are properly determined. Although this representation is greatly simplified, the key zone parameters (zone comfort conditions and HVAC energy use) can be simulated well [13,14].

With the increased use of building energy simulation for evaluating the effectiveness of energy conservation retrofits, calibration of simulation programs to measured data has been recognized as an important factor in substantiating how well a model represents the characteristics of a real building. The development of a step-by-step simplified model calibration procedure will allow building professionals to carry out the calibration procedure in substantially less time, making it practical for use in more applications. The ability to develop a calibrated simulation of buildings with multiple HVAC systems from short-term field measurements will also enable the use of calibrated simulation to accurately estimate the annual cooling and heating energy use from short-term measurements. An improved procedure will also increase the accuracy of the model calibration that can be achieved within practical time constraints significantly. The calibrated models can serve as diagnostic tools for building commissioning and optimization, provide energy baselines and potential energy savings data on energy projects, provide material for HVAC building energy analysis book publishers as an aid for developing more effective texts and training programs, and serve as a resource for the future development of HVAC system fault detection procedures.

Reddy et al. developed the procedure of calibrating detailed building energy simulation programs (DOE-2) with measured data [22,23] through ASHRAE funded project 1051-RP. A calibration procedure suitable for use with simplified engineering simulation models for commonly used HVAC systems has been developed through an ASHRAE-sponsored project (ASHRAE 1092-RP). The objectives of the project were:

- Develop a step by step simplified model calibration procedure to allow building professionals to project annual cooling and heating energy consumption of buildings with multiple HVAC systems from short-term field measurement data.
- Validate the step-by-step procedure using five case study buildings with an existing simulation program developed using the ASHRAE simplified energy simulation procedures (modified bin method and ASHRAE tool kits).

The ASHRAE project reports [19] also documents the scientific and engineering foundations of the simplified model calibration procedures. This paper presents the step by step calibration procedure developed and illustrates its use with a detailed case study.

2. General procedure

The general procedure developed adopts the definitions of [5] for calibration signatures and characteristic signatures. It builds on the procedure developed by [24] but uses building specific characteristic signatures instead of generalized characteristics signatures and a more detailed reconciliation with hourly data. It includes a much more detailed specification of data collection and calibration procedures, and is shown to be suitable for calibration to much shorter periods of measured data. The simplified model calibration procedure developed consists of three steps:

2.1. Step 1. Information collection

General building information, schedules, mechanical system information and control sequences, energy consumption data and bills must be collected in the first step.

2.2. Step 2. Site visit and short-term measurements

In this step, the information obtained from Step 1 is verified and the short-term measurement data is recorded. These measurements include in-situ one-time measurements, usually made using hand-held instruments, and short-term measurements of energy consumption data, for which instruments with data logging capabilities are set up and left in place to collect data for longer periods of time.

2.3. Step 3. Model calibration

In this step, the initial input for the model is determined and the model is calibrated using the developed characteristic signatures and calibration signatures.

Step 3.1 Determine the initial simulation inputs for the building energy simulation model

Step 3.1.1 Consolidate similar AHUs

Step 3.1.2 Determine the initial input values for each group

Step 3.2 Develop the calibration signatures and characteristic signatures

Step 3.2.1 Generation of calibration signatures

Wei et al. [24] found that calculating the differences between the measured heating and cooling consumption and those predicted by an un-calibrated simulation, normalizing these differences and plotting them as a function of ambient temperature, provides important information about the input variable change(s) needed to achieve calibration. Generate the calibration signatures.

A calibration signature is a normalized plot of the differences between measured energy consumption values and the corresponding simulated values as a function of outdoor air temperature.

Step 3.2.2 Develop characteristic signatures for the corresponding system type and climate

The characteristic signatures for a particular input parameter are defined as normalized plots of the differences between heating or cooling energy consumption values simulated using two different values of a particular input parameter, as a function of outdoor air temperature.

Step 3.3 Simplified model calibration using characteristic signatures and 24 h daily internal gain patterns

A two-level calibration method was developed. The first calibration level focuses on the weather dependence of the model. The second-level focuses on the time dependence of internal gains.

Initial input changes are made as indicated by the signatures, and the simulation is run again. The simulated values of heating and cooling consumption are compared with the measured values, and if the desired level of agreement has not been achieved, new calibration signatures are generated, and the procedure is repeated iteratively until the desired level of agreement has been achieved between simulated and measured values.

Please also refer to Fig. A2 in the Appendix for the 3-step flow diagram. The procedure is now illustrated by application to a case study building. Additional detail on the procedure and case study results are available in the RP-1092 Final Report [19].

3. Demonstration of the calibration procedure

A high-rise office building in Omaha was chosen to demonstrate the procedure in a case study. The simulation model is calibrated using two weeks of heating and cooling data following the calibration procedure. After model calibration, the calibrated model is used to simulate year 2004 hourly energy consumption and the results of this simulation are compared with the actual measured data.

3.1. Step 1. Information collection

General building information, schedules, mechanical system information and control sequences, energy consumption data and bills are collected in the first step.

Step 1.1 General building information

The high-rise office building is a commercial office building located in Omaha, Nebraska. This 43 story building was built in 2002, and the total conditioned area is 754,000 ft^2 (70,000 m^2). The current number of building occupants is 1537. The normal office hour is from 8:00 am to 5:00 pm

Step 1.2 Mechanical system information

Step 1.2.1 System operating schedule: 24 h a day, 7 days a week

Step 1.2.2 Primary system

The chilled water (CHW) and heating hot water (HW) are supplied from a remote central plant.

Step 1.2.3 Secondary system

- *Information for each AHU*: Eight main variable air volume (VAV) air-handling units (AHUs) with variable frequency drives installed serve most of the office areas in this building. One single-zone constant volume AHU serves the Winter Garden area of the building. Two heating-only constant volume AHUs (Make-up unit MUAH1-1&4) serve the garage. Three cooling-only constant volume AHUs (5U, 6U, &7U) serve the elevator equipment rooms.
- *Terminal boxes*: the eight main AHUs have VAV terminal boxes with hot water reheat. Other AHUs are constant air volume (CAV) systems.

Step 1.3 Energy consumption data

Step 1.3.1 The hourly outdoor air temperature data were obtained from the National Weather Service and hourly energy consumption data for CHW, HW, and whole building electricity (WBE) were obtained from the energy suppliers

Step 1.3.2 Monthly energy bills were obtained from the energy supplier

3.2. Step 2. Site visit and short-term measurement

In this step, the information obtained from Step 1 is verified and the short-term measurement data are recorded.

Step 2.1 Short-term measurements

Step 2.1.1 Measurement period

For Omaha weather conditions, the period from the end of March to the end of April is recommended because a sufficient range of variation in ambient temperature and humidity conditions and hence in heating and cooling energy consumption data can be obtained for calibration. In addition, the mean value of monthly average for April is 51 °F, which is the closest one to the average of 12-month mean value (50.7 °F). An implementation of the modified bin method (AirModel, [17]) was used for this case study and the simulation was calibrated to the two weeks of data for April 1–14, 2003.

Step 2.1.2 Measurement method

A Electricity: measured by the building utility meter

B Cooling energy consumption: measured using chilled water flow rate recorded by the owner's chilled water flow meter, and RTD sensors for the supply and return chilled water temperatures.

C Heating energy consumption: measured using hot water flow rate recorded by the owner's hot water flow meter, and RTD sensors for the supply and return hot water temperatures.

D Measurement results

Fig. 1 shows the measured Omaha weather data for April 1–14 2003. The measured heating and cooling consumption vs. dry-bulb temperature for this period can be seen in Fig. 2.

Step 2.2 A site visit was conducted to verify the mechanical system and schedule information

The AHU and terminal box data from Step 1 were verified.

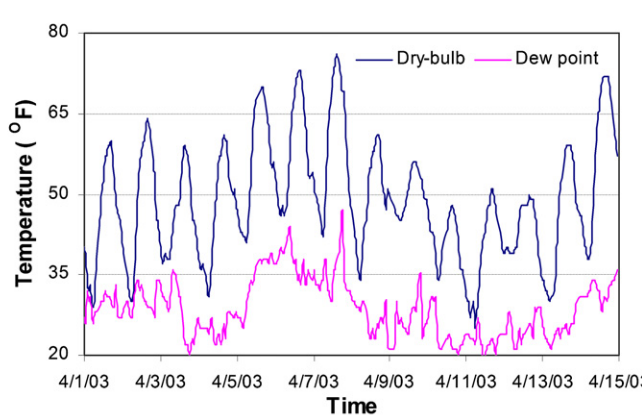

Fig. 1. Omaha, Nebraska dry-bulb and dew-point temperatures for the calibration period.

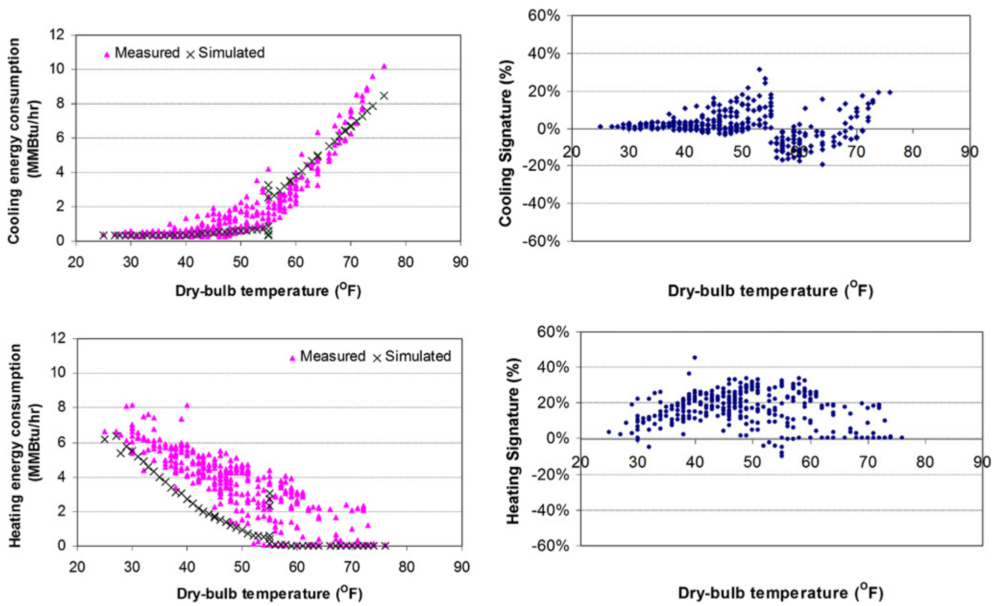

Fig. 2. Comparison of measured cooling and heating consumption with initial simulated values and initial cooling and heating calibration signatures.

3.3. Step 3. Model calibration

Step 3.1 Determine the initial simulation inputs of the building energy simulation model

Step 3.1.1 Consolidate the similar AHUs

1) Consolidate AHUs according to the air modulation type

Eight main air-handling units (AHUs) serve most of the office areas in this building. The AHUs serving office areas, which include AHUs 1L, 2L, 3L, 4L, 1U, 2U, 3U and 4U, can be consolidated into one AHU for the simulation. The heating-only constant volume AHUs serving the garage can also be consolidated into one AHU. Likewise, three cooling-only constant volume AHUs serving the elevator equipment rooms can be consolidated as one AHU. This results in four AHUs included in the simulation:

A. G-1(Main air-handling units) single-duct VAV system with reheat (SDRHVAV)
B. G-2 (Winter Garden air-handling unit) single-zone CAV (SZCAV)
C. G-3 (Garage air-handling units). Single-duct and heating only (SDH)
D. G-4 (Elevator equipment rooms): Single-duct and cooling only (SDC)

2) Divide the area served by each AHU into two zones and record the interior zone fraction for each AHU

Step 3.1.2 Determination of the initial input values for each AHU simulated

The input parameters used in the initial simulation are summarized in Table 1. They were measured, approximated or retrieved from design drawings and control sequences.

Step 3.2 Develop the calibration signatures and characteristic signatures

Step 3.2.1 Generation of calibration signatures

1) Run the simulation model using the initial inputs
2) The residuals (differences between measured and simulated values), the root mean square errors (RMSE) and the mean bias errors (MBE) were calculated for the initial simulation. The RMSE was 0.68 MMBtu/hr (199 kW) for cooling and 2.28 MMBtu/hr (668 kW) for heating energy consumption. The MBE was 0.14 MMBtu/hr (43 kW) for cooling and 1.97 MMBtu/hr (579 kW) for heating. Fig. 2 compares the simulated heating and cooling consumption with the measured values and shows the calibration signatures for the initial simulation results.

Step 3.2.2 Develop characteristic signatures for the corresponding system type and climate

The measured weather data for this building was used in to generate the characteristic signatures. The input

Table 1
Summary of AHU group information.

AHU	G-1	G-2	G-3	G-4
Type	SDRH	SZ	SDH	SDC
VAV/CAV	VAV	CAV	CAV	CAV
Design flow	598,000 CFM (282,200 L/s)	40,000 CFM (18,900 L/s)	21,000 CFM (9900 L/s)	6400 CFM (3020 L/s)
Minimum speed (%)	30%	n/a	n/a	n/a
Econ. range (min/max)	40/68 °F (4.4/20 °C)	40/68 °F (4.4/20 °C)	n/a	n/a
Min. OA	108,000 CFM (51,000 L/s)	4000 CFM (1890 L/s)	21,000 CFM (9910 L/s)	6400 CFM (3020 L/s)
Space function	Offices	Sun space	Garage	Elevators
Space occupancy schedule	8am–5pm	8am–5pm	n/a	8am-5pm
AHU schedule	24/7	24/7	24/7	24/7
Lighting schedule	24/7	24/7	24/7	24/7
T_c	55 °F (12.8 °C)	Reset	n/a	n/a
T_m	55 °F (12.8 °C)	Reset	n/a	n/a
T_r (Clg/Htg)	74/72 °F (23/22 °C)	74/72 °F (23/22 °C)	60 °F(H) (15.6 °C)	74 °F(C) (23.3 °C)
Terminal box (TB) type	VAV/RH	n/a	n/a	n/a
TB minimum airflow ratio %	20	n/a	n/a	n/a
Envelope area	163,000 ft^2 (15,100 m^2)	6000 ft^2 (557 m^2)	27,400 ft^2 (2550 m^2)	n/a
Window area	108,600 ft^2 (10,090 m^2)	19,900 ft^2 (1850 m^2)	6860 ft^2 (637 m^2)	n/a
Floor area	684,300 ft^2 (63,600 m^2)	43,500 ft^2 (4040 m^2)	106,100 ft^2 (9860 m^2)	n/a
Interior zone %	70	0	–	100

parameters that are recommended for generating the characteristic signatures include: building envelope heat transfer coefficients, internal heat gain, outside air intake for interior zones and exterior zones, solar radiation load, air infiltration, cold and hot deck temperatures, space temperature, and maximum and minimum airflow rates. These calibration parameters have a significant influence on energy consumption and are found to be the most sensitive input parameters (Mottillo, [26]) or are those in which the authors have frequently seen input errors. Appendix II shows examples of the characteristic signatures for this building. A complete set of the characteristic signatures for this building are available in Appendix B-1 of Liu et al. [19].

Step 3.3 Simplified model calibration using characteristic signatures and 24-h daily pattern

Step 3.3.1 First level calibration – using characteristic signatures

This calibration method requires some engineering sense of appropriate values, but can significantly speed up the process, even for engineers without a great deal of simulation experience. The use of calibration signatures and characteristic signatures helps decide which parameter(s) should be changed and gives some indication of the size of change(s) required. The example illustrates the process.

1). Example of the use of characteristic signatures

Iteration I. The calibration signatures in Fig. 2 are compared with the characteristic signatures in Appendix II corresponding to this building in Omaha. Note that the calibration signature for heating has positive values and has average values near 15%. The heating calibration signature is similar to an inverted version of the characteristic signature for internal heat gain in Appendix II. The cooling calibration signature also exhibits some similarity to the characteristic signature.

In the characteristic signatures of Appendix II, the internal heat gain increased 0.2 W/ft^2, which caused heating to decrease by about 3%. It also caused cooling to increase by about 1% above 60 °F. The heating calibration signature shows a change of about 15% suggesting that more than 0.2 W/ft^2 change in internal gain is needed. Different increments were tested and the best result was obtained by decreasing the internal heat gain from 1.7 W/ft^2 to 1.0 W/ft^2.

After this change, the calibration signature for heating in Fig. 3 has decreased for the temperatures lower than 55 °F (12.8 °C). However the value of the cooling signature has increased appreciably for temperatures higher than 55 °F (12.8 °C). The heating RMSE decreased from 2.28 MMBtu/h (670 kW) to 1.71 MMBtu/h (502 kW), and the heating MBE dropped from 1.97 MMBtu/h (579 kW) to 1.18 MMBtu/h (347 kW). The cooling RMSE increased from 0.68 MMBtu/h (200 kW) to 1.02 MMBtu/h (301 kW), and the cooling MBE increased from 0.14 MMBtu/h (43 kW) to 0.65 MMBtu/h (192 kW). But we don't need worry about the cooling signature getting worse; this will be addressed in the next step.

Iteration II. The calibration signatures in Fig. 3 are compared with the characteristic signatures in Appendix II, Fig. A1 corresponding to this building in Omaha. Note that the calibration signature for cooling has positive values and positive slope. It starts near zero at 45 °F and reaches 40% at higher temperatures. The heating calibration signature has average values near 10%. The cooling calibration signature is similar to an inverted version of the characteristic signature for minimum airflow and to the signature for supply air temperature in Appendix II. The change induced by changing minimum airflow is larger, so we chose to increase the minimum airflow rate.

In the characteristic signatures of Appendix II, a minimum airflow decrease of 0.06 cfm/ft^2 caused a decrease in cooling from 0% to 8% at temperatures above 55 °F. It also caused a decrease in heating from 0% to 5% at temperatures above 50 °F. This suggests that minimum airflow rate should be increased. Different increments were tested and the best result was

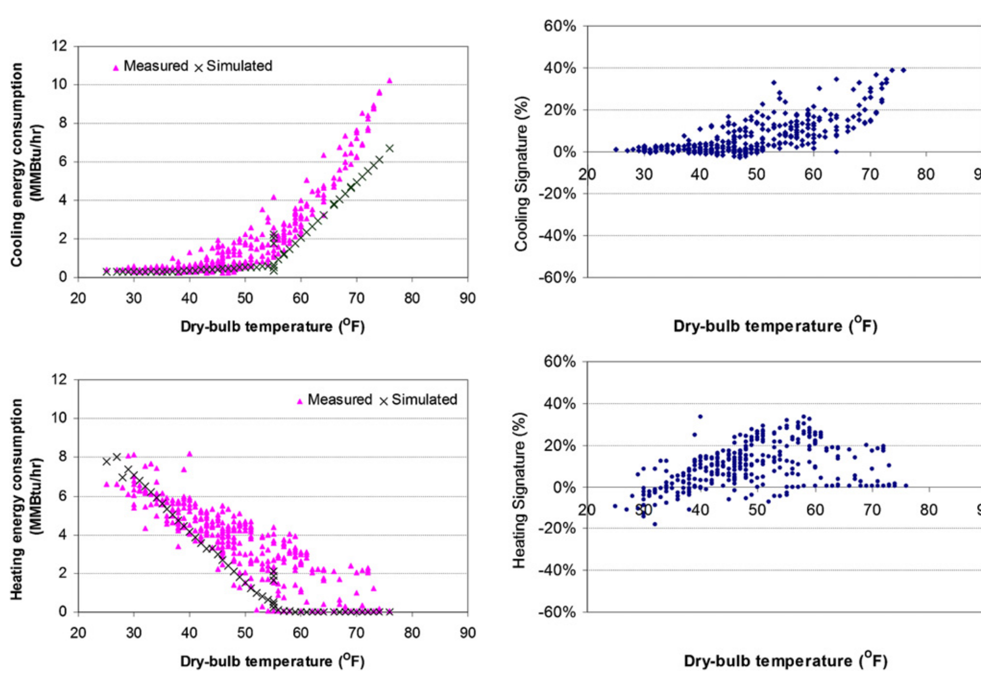

Fig. 3. Comparison of measured cooling and heating consumption with simulated values and cooling and heating calibration signatures after reducing internal heat gain to 1.0 W/ft^2.

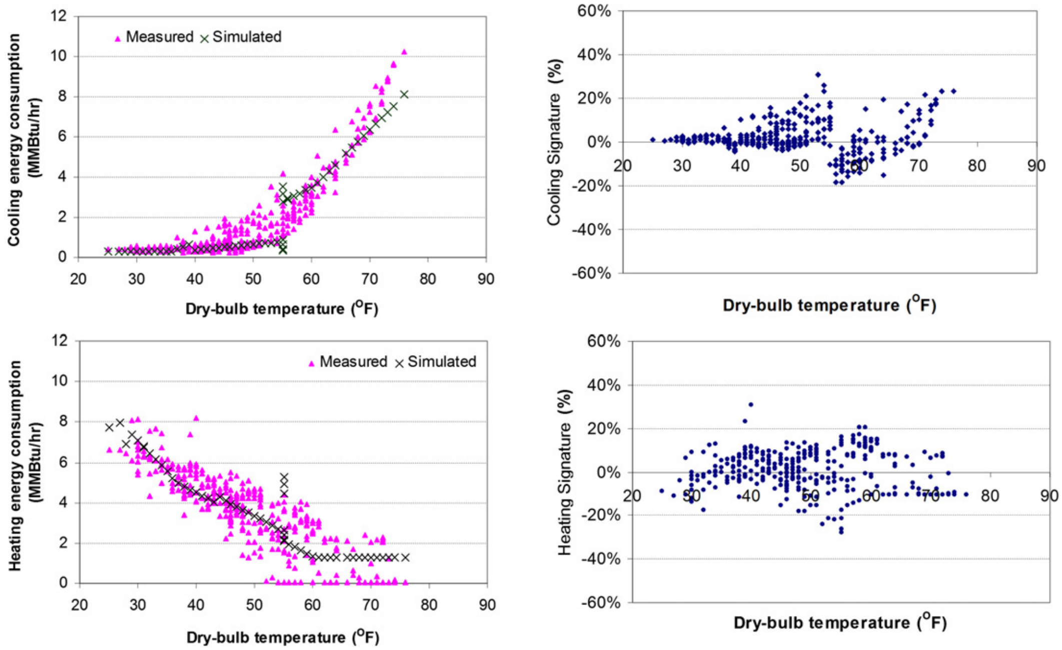

Fig. 4. Comparison of measured cooling and heating consumption with simulated values and cooling and heating calibration signatures after minimum airflow rate was increased to 0.35 cfm/ft^2.

obtained by increasing the minimum airflow rate from 0.20 cfm/ft^2 to 0.35 cfm/ft^2.

After this change, the calibration signature for heating in Fig. 4 generally varies about zero while the size of the signature for cooling has decreased for temperatures higher than 55 °F (12.8 °C). The cooling RMSE decreased from 1.02 MMBtu/h (301 kW) to 0.69 MMBtu/h (203 kW), and the cooling MBE dropped from 0.65 MMBtu/h (192 kW) to 0.16 MMBtu/h (47 kW). The heating RMSE decreased from 1.71 MMBtu/h to 1.07 MMBtu/h, and the heating MBE dropped from 1.18 MMBtu/h (347 kW) to 0.08 MMBtu/h (24 kW).

After these two iterations, median values of both calibration signatures approach zero for heating and cooling at most temperatures. No characteristic signature matches them closely, so the 2nd level calibration is carried out.

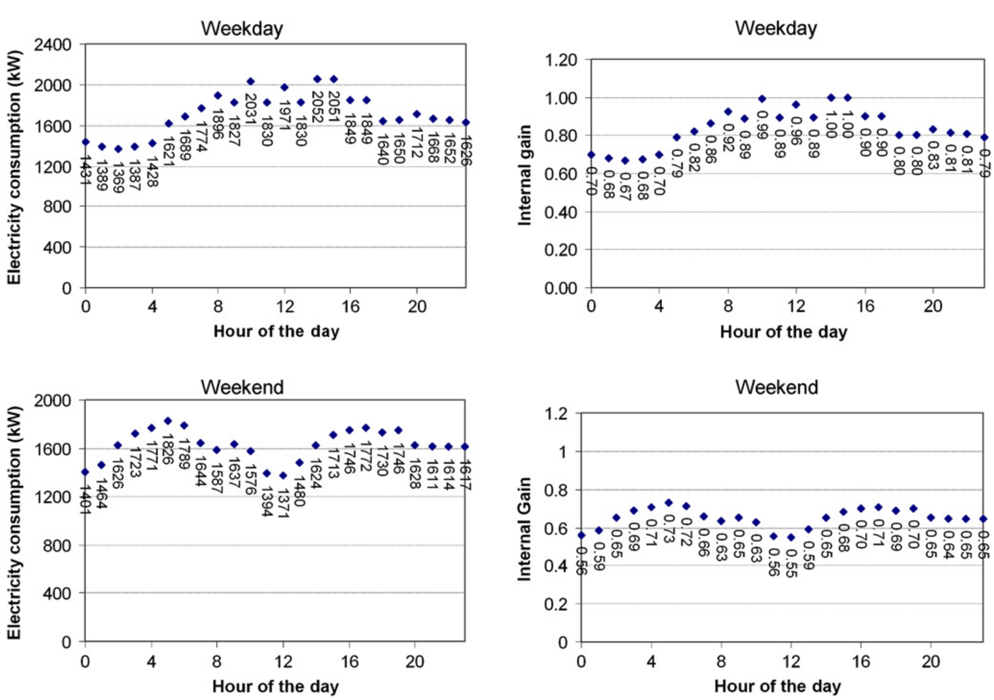

Fig. 5. Internal gain (kW) and internal gain load shape for weekdays and weekends.

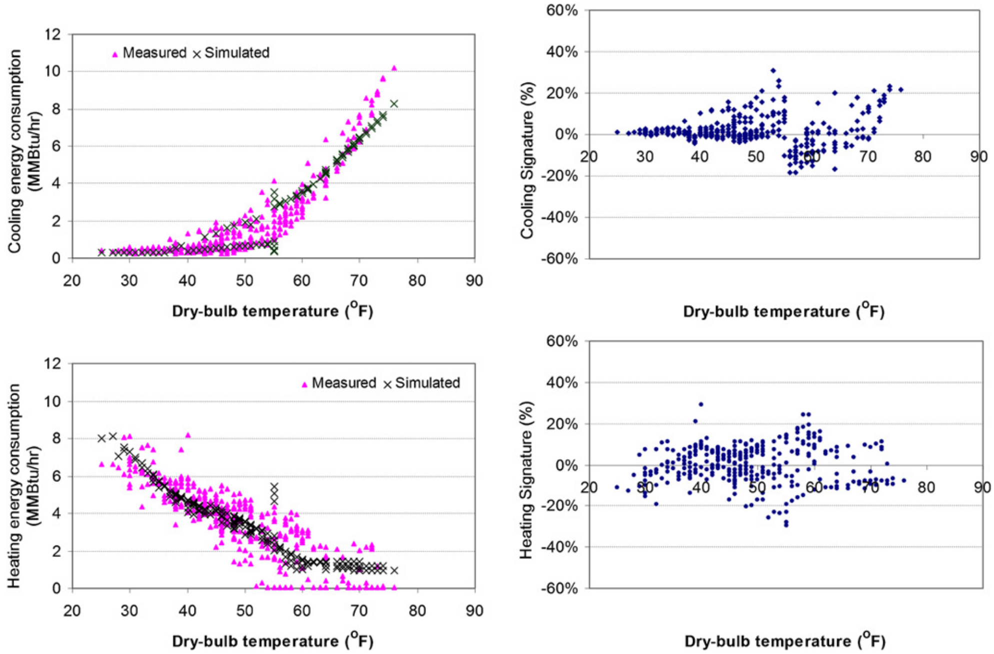

Fig. 6. Comparison of measured cooling and heating consumption with simulated values and cooling and heating calibration signatures after the peak internal gain was adjusted to 1.2 W/ft^2.

Step 3.3.2 Second-level calibration

The objective of the second-level calibration is to fine-tune the calibration using daily patterns of energy consumption.

Step 3.3.2.1 Internal gain daily pattern

The model was then fine-tuned using the daily internal gain pattern. This was achieved by introducing the daily electricity consumption profile, shown on the left side of Fig. 5, and calculated from the average hourly variations of electricity consumption in this building, shown on the right side of Fig. 5. The available metered data for electricity is Whole Building Electricity consumption (WBE). The simulated HVAC electricity consumption is very small compared to the WBE. Therefore the WBE daily pattern can be used to calculate the internal gain profile. Fig. 5 shows the internal gain profile vs. the time of day for weekdays and weekends. Fig. 5 shows that the off peak electricity command is still significant. This is because the HVAC, lighting and data center are all operated 24/7. The figure on the right side connects the average values for electricity consumption for each hour of the day. The internal gain profile (right side) is calculated from the average electricity consumption divided by the maximum hourly average electricity consumption in the simulation period (2502 kW). The daily internal gain profile was defined for each hour as the ratio of internal gain to maximum internal gain.

Therefore, instead of using an average heat gain of 1.0 W/ft^2 for each hour of the day, a maximum internal gain will be used along with the internal gain profiles of Fig. 5. The only parameter that needs to be adjusted is maximum internal gain. Different values were tested and the best result was obtained with 1.2 W/ft^2. Fig. 6 shows the results after this change. The RMSE for cooling decreased from 0.69 MMBtu/h (203 kW) to 0.67 MMBtu/h (197 kW). The MBE for cooling decreased from 0.16 MMBtu/h (47 kW) to 0.13 MMBtu/h (40 kW). The RMSE for heating decreased from 1.07 MMBtu/h (314 kW) to 1.01 MMBtu/h (297 kW). The MBE for heating decreased from 0.08 MMBtu/h (24 kW) to 0.04 (12 kW) MMBtu/h.

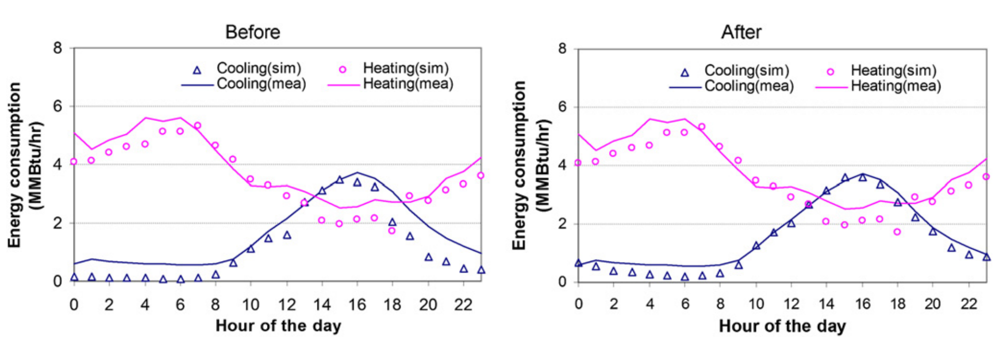

Fig. 7. Daily cooling and heating patterns.

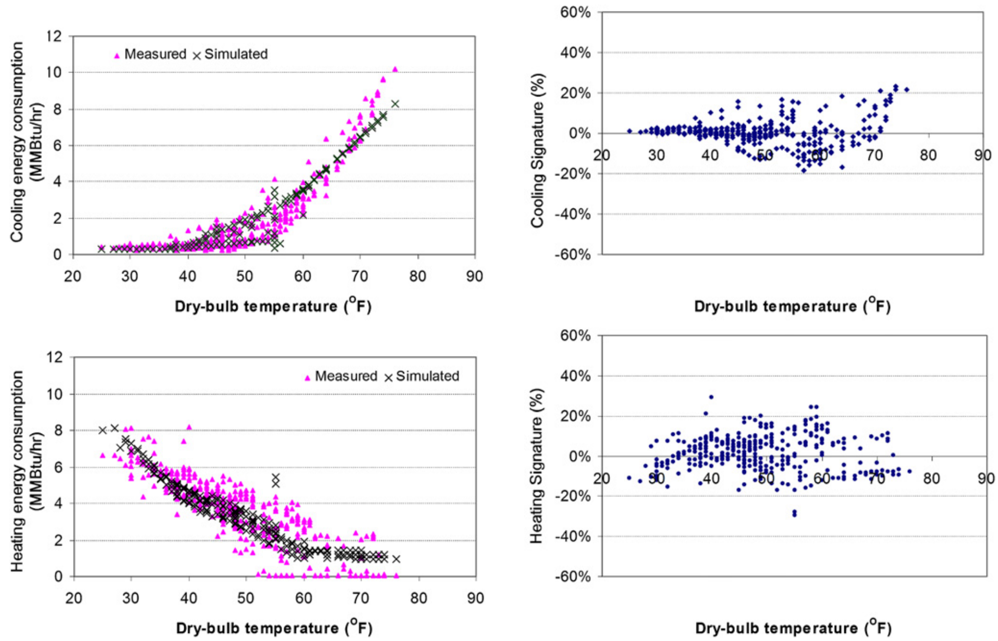

Fig. 8. Comparison of measured cooling and heating consumption with simulated values and cooling and heating calibration signatures after second-level calibration.

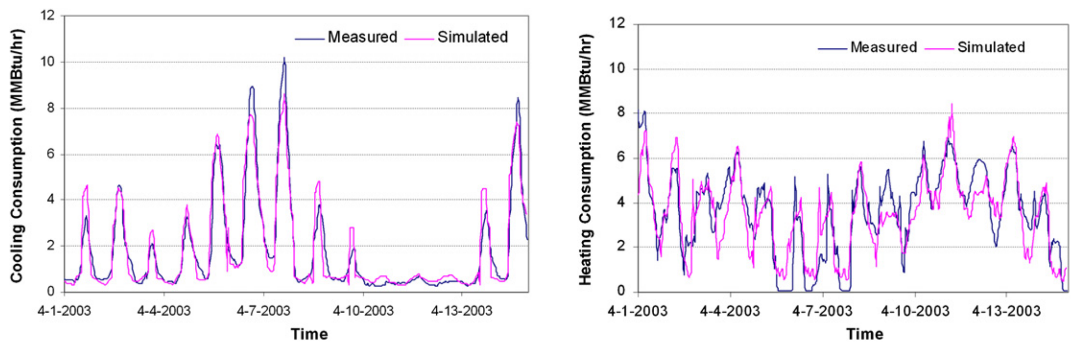

Fig. 9. Energy consumption for simulation period.

Step 3.3.2.2 Cooling/heating daily patterns

The daily cooling and heating patterns for the measured data can be obtained by dividing the average hourly heating/cooling energy consumption by the maximum heating/cooling energy consumption. A method similar to that used to adjust the internal gain pattern can be applied to the daily cooling and heating patterns in the simulation. Based on the daily cooling/heating patterns, a proper room temperature reset schedule, outside air intake schedule, supply air temperature schedule and other schedules, and time-dependent heat gains can be identified and corrected. Fig. 7 (left side figure) shows the daily cooling and heating energy patterns after the internal gain adjustment. As can be seen from the left side of Fig. 7, the simulated energy consumption is much less than the measured cooling energy consumption during unoccupied hours (6:00 pm to 8:00 am). A possible reason for the cooling pattern shown in Fig. 7 is that the economizer is disabled during unoccupied hours. The building has different outdoor air intake schedules for the

Table 2
Summary of calibration steps.

Simulation parameter and iteration	Cooling (MMBtu/h)/(%)		Heating (MMBtu/h)/(%)	
	RMSE/CV (RMSE)	MBE/NMBE	RMSE/CV (RMSE)	MBE/NMBE
First-level calibration				
Initial simulation	0.68/38%	0.14/8%	2.28/63%	1.97/55%
Iteration 1: Internal heat gain: 1.7 → 1.0 W/ft^2	1.02/57%	0.65/37%	1.71/47%	1.18/33%
Iteration 2: Minimum airflow rate: 0.20 → 0.35 CFM/ft^2	0.69/38%	0.16/9%	1.07/30%	0.08/2%
Second-level calibration				
Internal gain profile calibration: • Internal gain: 1.0(avg) → 1.2 W/ft^2 (max) • Occupancy schedule	0.67/37%	0.13/7%	1.01/29%	0.04/1.1%
Cooling/heating daily pattern calibration: Disable the economizer during unoccupied hours	0.57/31%	0.01/1%	0.98/28%	0.02/0.6%

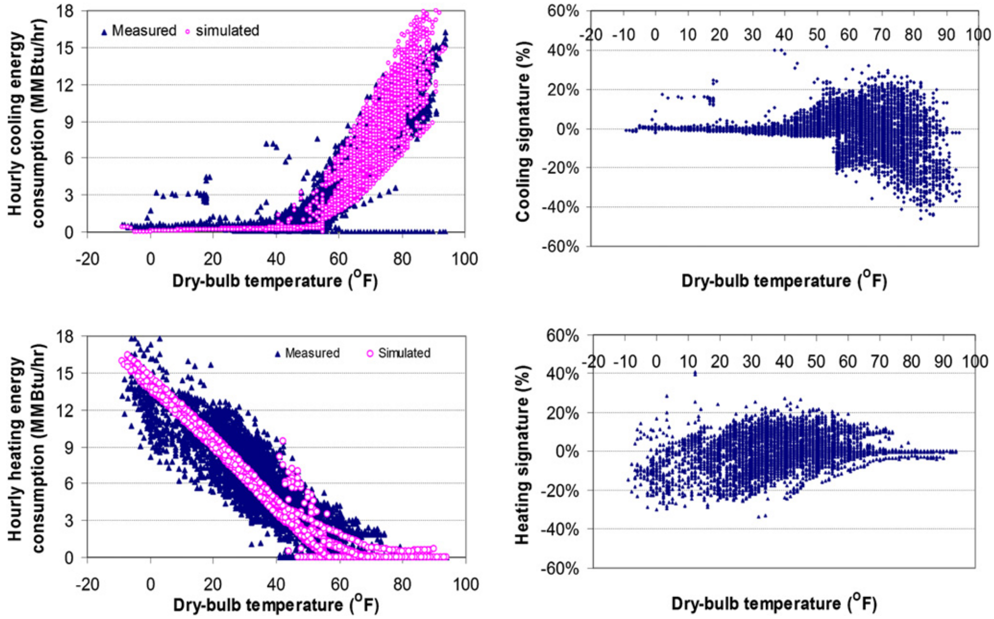

Fig. 10. Hourly cooling and heating simulation charts.

occupied and unoccupied hours. The energy consumption during unoccupied hours was then simulated with the economizer off.

After model recalibration, the right side of Fig. 7 shows the energy consumption patterns after the recalibration. It shows that the simulated daily cooling pattern was improved after the schedule adjustment. Fig. 8 shows the energy consumption vs. outdoor air temperature after this change. The RMSE for cooling decreased from 0.67 MMBtu/h (197 kW) to 0.57 MMBtu/h (168 kW). The MBE for cooling decreased significantly from 0.13 MMBtu/h (40 kW) to 0.01 MMBtu/h (3 kW). The RMSE for heating decreased from 1.01 MMBtu/h (297 kW) to 0.98 MMBtu/h (288 kW). The MBE for heating decreased from 0.04 MMBtu/h (12 kW) to 0.02 MMBtu/h (6 kW). The improvement is not as significant compared with the 1st level calibration because this is the fine-tuning process and the model has been highly calibrated already.

Step 3.4 Check the validation of the calibrated model

The final comparisons between measured data and simulated consumption during the calibration period are shown in Figs. 8 and 9. Fig. 9 shows a time series comparison of measured and simulated values during the calibration period. Table 2 summarizes the statistical measures of the differences between measured and simulated heating and cooling consumption for each step of the calibration process.

The RMSE for cooling and heating has been reduced from 0.68 MMBtu/h (200 kW) and 2.28 MMBtu/h (670 kW) to 0.57 MMBtu/h (168 kW) and 0.98 MMBtu/h (288 kW), respectively, compared with the initial simulation. The MBE for cooling and heating has been reduced from 0.14 MMBtu/h (43 kW) and 1.97 MMBtu/h (579 kW) to 0.01 MMBtu/h (3 kW) and 0.02 MMBtu/h (6 kW), respectively. This shows that the two-level calibration procedure improves the agreement between the simulation and the measured data significantly. Because the model matches the measured data well for the two week data collection period in April, the model was then used to simulate the building consumption for the period from January 1, 2004 to December 30, 2004. Fig. 10 shows the hourly simulation results with the calibration signatures. The CV(RMSE) and NMBE results for this case can be seen in Table 3.

As can be seen from Fig. 10, the heating calibration signature is generally in the range of ±20%. However, the hourly CV(RMSE) for both the CHW and HW are outside the ASHRAE suggested tolerances (ASHRAE Guideline 14-2001). And there are many bad data points in the hourly measurement data for 2004. Larger differences occurred in the winter of 2004 due to operational problems such as the economizer malfunction. These differences were circled in the whole year time series comparison charts (please refer to the RP-1092 report for details). However, if we compare the accumulated hourly simulation results for each month with the monthly bills, the CV(RMSE) for CHW and HW are reduced to 10.3% and 3.7% for cooling and heating, respectively, which is in the ASHRAE recommended tolerance range. It also shows monthly NMBE values of 2.2% and 1.4% for cooling and heating respectively, which are well below the 10% values considered acceptable in ASHRAE Guideline 14 [1]. Fig. 11 shows the monthly measured and simulated energy consumption. As can be seen by the figure, the monthly data match very well. Therefore we can use this calibrated model to simulate the monthly heating and cooling energy consumption in a higher confidence.

Table 3
Calibration results.

	CHW (2 weeks)	HW (2 weeks)	CHW (1 year)	HW (1 year)	CHW (monthly)	HW (monthly)
CV (RMSE)	31%	28%	44%	41%	10.3%	3.7%
NMBE	1%	0.6%	−5%	0.1%	2.2%	1.4%

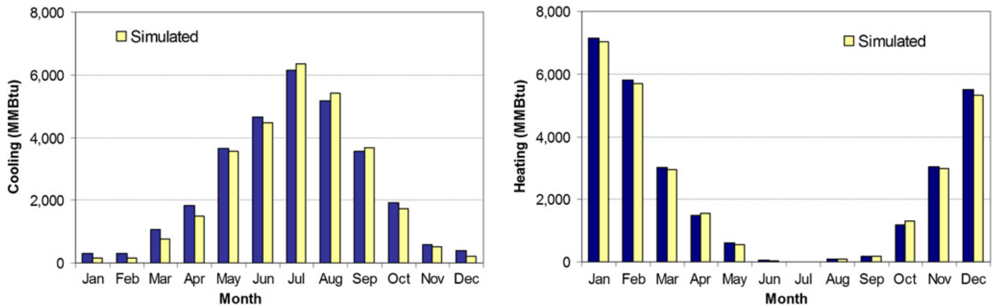

Fig. 11. Comparison of monthly bills.

This calibrated model has been used to calculate the savings potential for different energy conservation measures (ECMs).

4. Conclusions

Based on the use of the RP-1092 calibration procedure in this case study:

1) The systematic two-level calibration procedure developed in RP-1092 and presented in this paper dramatically reduced the differences between simulated and measured consumption results, even when the initial simulation used inputs based on careful field measurements. Normalized mean bias error was reduced from 8% to 1% and from 55% to 0.6% for cooling and heating, respectively. Hourly CV(RMSE) values were reduced from 38% to 31% and from 63% to 28% for cooling and heating, respectively.
2) The model calibration is not just data matching. The model must be physically calibrated. The two-level calibration procedure provides a good approach for the model calibration.
3) Comparison of simulated cooling and heating with measured cooling and heating energy consumption against time of day is a very important step in model calibration. This comparison will identify the proper time schedules for supply air temperature, room temperature, outside air intake, and other parameters. The improvement from this step is not as significant as that of the 1st level calibration steps because this is a fine-tuning process and the model has been significantly calibrated before this step is implemented.

This procedure was also applied to four other buildings. The report under 1092-RP [19] presents the conclusions of the project and discusses the method's applicability to various building types, systems and the impact of data availability.

5. Discussion

The authors are agree with the reviewer's comments.

- This is an over-simplified example to demonstrate the calibration procedure. The actual number of simulation runs depends on the building& systems type, data availability, allowed time frame, practitioners' experience and skills.
- This model can be used to predict monthly energy consumption with acceptable accuracy. Satisfying ASHRAE criteria on an hourly basis seems very difficult and not always meaningful (especially when using a simplified simulation model and typical operation profiles). Checking of the calibration with more global data (such as monthly utility bills) should be sufficient for most of the applications.

The following challenges can be considered for further study:

1) An additional improvement to the method could consist in integrating sensitivity issues (helping in ordering the parameters by order of influence). This would allow cross-checking the information given by calibration and characteristics signatures.
2) Developing a guideline for how to decide which parameter should be chosen for the similar characteristic signatures in the 1st level calibration.
3) Can we develop a physical signature for those input parameters in the 2nd level calibration just like the characteristic signature, so that the user can decide which parameter should be chosen for improving the CHW/HW daily pattern in the 2nd level calibrations?
4) This procedure is for simplified model calibration. Is it possible to develop a similar procedure for detailed model calibration?

Acknowledgements

The authors gratefully acknowledge ASHRAE and the valuable suggestions and recommendations of the Project Monitoring Committee members for RP 1092 (Dr. Hashem Akbari, Mr. Jim Carlson, and Mr. Ken Gillespie) in the performance of this work.

The authors gratefully acknowledge Dr. David Claridge for his review and revisions. The team also appreciates the assistance of Ms. Jinrong Wang and Mr. Ken Hansen from the Omaha Public Power District in coordinating with the building owners. We also thank all of the building engineers and owners who provided the team with the case study buildings for this project.

Appendix I

The Root Mean Square Error (RMSE) and the mean bias error (MBE) are the most frequently used statistical metrics to assess improvement in calibration and model accuracy for a calibrated model.

- RMSE for residuals

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \text{residual}_1^2}{n-2}}$$

where n is the number of the data points; the Residual = (Simulated energy consumption) − (Measured energy consumption).

The RMSE is a good measure of the overall magnitude of the errors. It reflects the size of the errors and the amount of scatter, but does not directly reflect any overall bias in the data. The RMSE would be a good metric of how "good" the simulation is for calibration purposes.

- MBE for residuals

$$MBE = \frac{\sum_{i=1}^{n} \text{residual}_i}{(n-p)}$$

with the MBE, positive and negative errors cancel each other, so the MBE is an overall measure of data bias.

- The coefficient variation of RMSE (CV(RMSE)) and normalized MBE (NMBE) are calculated by the following equations:

$$CV(RMSE) = \frac{RMSE(\text{residuals})}{\text{Average\_measured\_energy}} \times 100\%$$

$$NMBE = \frac{MBE(\text{residual})}{\text{Average\_measured\_energy}} \times 100\%$$

Appendix II. Building specific characteristic signatures

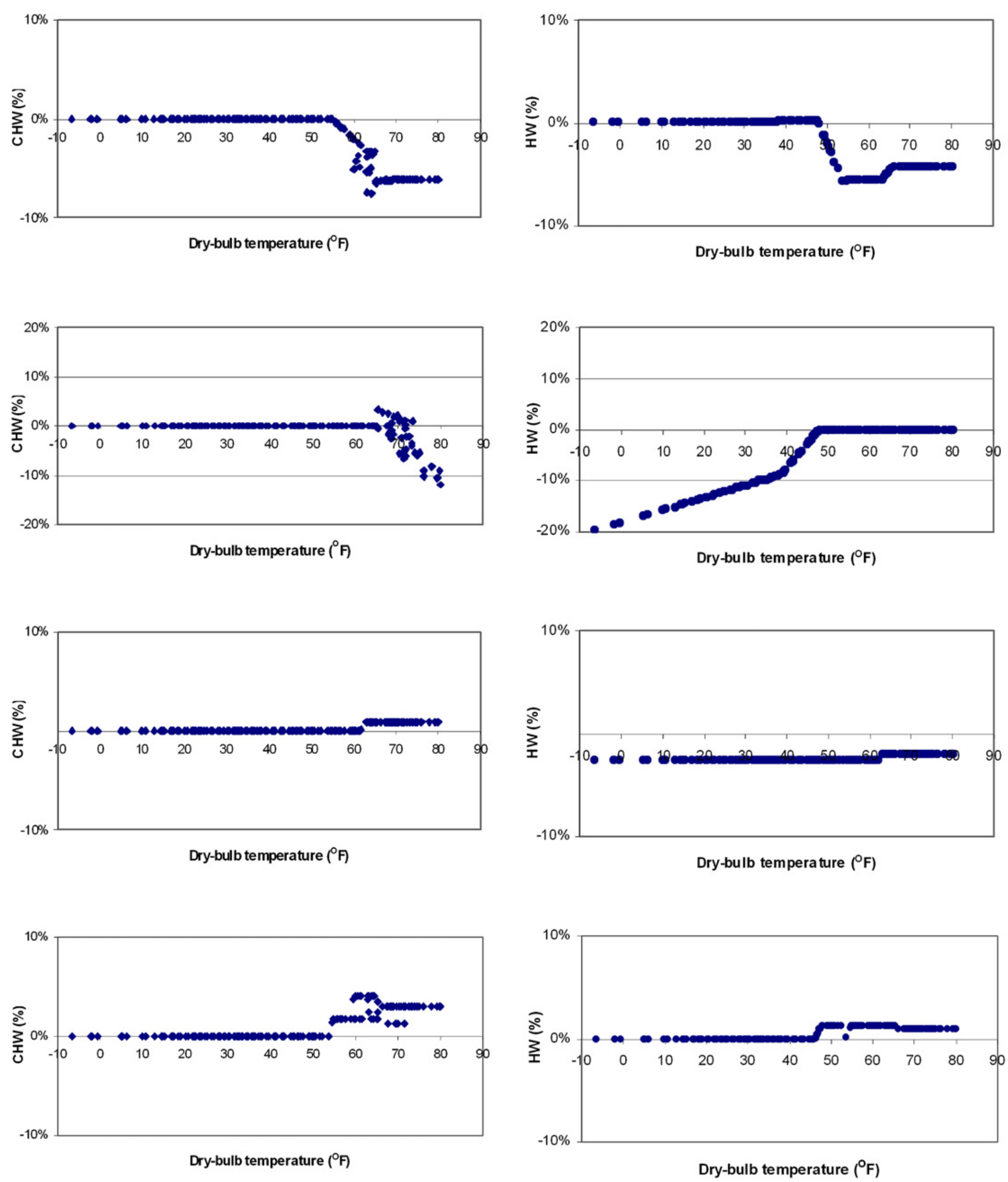

Fig A1. Characteristic signatures (samples).

Appendix III

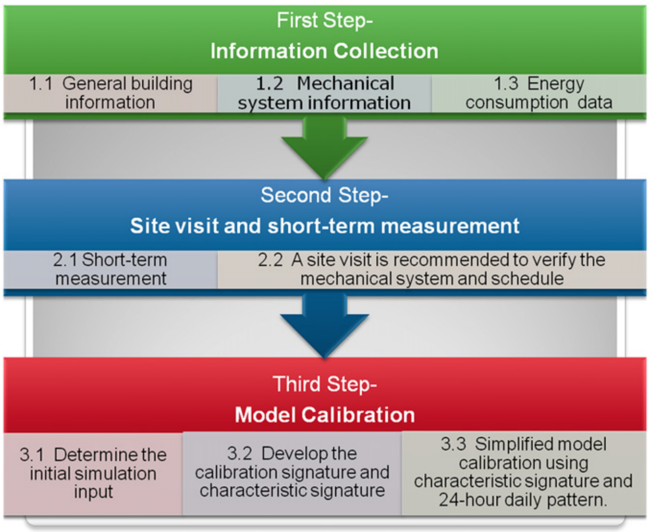

Fig A2. Calibration 3-step flow diagram.

References

[1] ASHRAE. Guideline 14-2002, Measurement of energy and Demand savings. Atlanta: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.; 2002. p. 41.
[2] Ayres MJ, Stamper E. Historical development of building energy calculations. ASHRAE Transactions 1995;101(1):47–55.
[3] Bou-Saada T, Haberl J, A weather-day typing procedure for disaggregating hourly end-use loads in an electrically heated and cooled building from whole-building hourly data. Proceedings 30th IECEC. Orlando, Florida. July 31–August 3, 1995, p.349–356.
[4] Brotherton T, Kreider J, Claridge DE, Norford LK. A multi-climate comparison of the simplified ASHRAE building energy consumption model with DOE-2 results. ASHRAE Transactions 1987;93(2):600–20.
[5] Claridge DE, Bensouda N, Lee SU, Wei G, Heinemeier K, Liu M. Manual of procedures for calibrating simulations of building systems. submitted to the California energy commission public interest energy research program, Report HPCBS#E5P23T2b, 96 pp. http://buildings.lbl.gov/hpcbs/pubs/E5P23T2b.pdf; October, 2003
[6] Diamond S, Hunn B. Comparison of DOE-2 computer program simulations to metered data from seven commercial buildings. ASHRAE Transactions 1981;87(1):21–7.
[7] Haberl JS, Bronson JD, O'Neal DL. An evaluation of the impact of using measured weather data versus TMY weather data in a DOE-2 simulation of an existing building in central Texas; 1995. ESL Report No. ESL-TR-93/09-02, College Station, TX.
[8] Hinchey SB, Influence of thermal zone assumptions on DOE-2 energy use estimations of a commercial building, M.S. Thesis. College Station, TX: Mechanical Engineering Department, Texas A&M University, 1991.
[9] Hittle D. The building loads analysis and system Thermodynamics program, BLAST. Champaign, Illinois: US Army Construction engineering research Laboratory; 1977.
[10] Hsieh ES, Calibrated computer models of commercial buildings and their role in building design and operation, M.S. thesis. PU/CEES Rpt No. 230. Princeton, NJ: Princeton University, 1988
[11] Hunn BD, Banks JA, Reddy SN. Energy analysis of the Texas capitol restoration. The DOE-2 User News 1992;13(4):2–10.
[12] Kaplan MB, Caner P, Vincent GW. Guidelines for energy simulation of commercial buildings. Proceedings of the ACEEE 1992 Summer Study on Energy Efficiency in Buildings 1992;1:137–47.
[13] Katipamula S, Claridge DE. Use of simplified systems model to measure retrofit energy savings. Transactions of the ASME Journal of Solar Energy Engineering 1993;115:57–68.
[14] Knebel DE. Simplified energy analysis using the modified bin method. Atlanta, GA: ASHRAE; 1983.
[15] Kusuda T. Comparison of energy calculation procedures. ASHRAE Journal 1981;23(8):21–4.
[16] LBL. DOE-2 user guide. version 2.1, LBL report No. LBL-8689 Rev. 2. Berkeley, California: Lawrence Berkeley Laboratory; 1980.
[17] Liu M. User's manual for air side simulation programs (AirModel). College Station, Texas: Energy Systems Laboratory, Mechanical Engineering Department, Texas A&M University; 1997.
[18] Liu M, Claridge DE. Use of calibrated HVAC system models to optimize system operation. ASME Journal of Solar Energy Engineering 1998;120:120–31.
[19] Liu M, Liu G, Claridge DE, Haberl JS. Development of procedures to determine in-situ performance of commonly used HVAC systems. ASHRAE research project report 1092-RP; 2006.
[20] Manke JM, Hittle DC, Hancock CE, Calibrating building energy analysis models using short term test data. Proceedings of the 1996 International ASME Solar Energy Conference. San Antonio, TX, 1996, pp. 369–378
[21] McLain HA, Leigh SB, MacDonald JM. Analysis of savings due to multiple energy retrofits in a large office building. ORNL Report No. ORNL/CON-363. Oak Ridge, TN: Oak Ridge National Laboratory; 1993.
[22] Reddy TA, Maor I, Panjapornpon C. Calibrating detailed building energy simulation programs with measured data-part I: general methodology (RP-1051). HVA&R Research 2007a;13(2):221–41.
[23] Reddy TA, Maor I, Panjapornpon C. Calibrating detailed building energy simulation programs with measured data-Part II: application to three case study office buildings (RP-1051). HVAC&R Research 2007b;13(2):243–65.
[24] Wei G, Liu M, Claridge DE, Signatures of heating and cooling energy consumption for typical AHUs. The eleventh symposium on improving building systems in hot and humid climates proceedings. Fort Worth, Texas, June 1–2, 1998, pp. 387–402
[25] Clarke JA, Strachan PA, Pernot C. An approach to the calibration of building energy simulation models. ASHRAE Transactions 1993;99(2):917–27.
[26] Mottillo M. Sensitivity Analysis of energy simulation by building type. ASHRAE Transaction, Cincinnati 2001;107(2):721–32.